App. 2,3

LHC INSERTIONS WITH OFFSET QUADRUPOLES

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Abstract. A new style of insertion for proton-proton colliders is proposed. By offsetting the quadrupoles, they can be used both for focusing and for separating the beams. This insertion can provide at least twice the luminosity of that of the previous proposals.

Introduction

In a high energy proton-proton collider with bunched beams the interaction regions are inherently difficult since they must satisfy two conflicting requirements. The beams must be focused to the smallest possible spot size so the quadrupoles must therefore be close to the crossing point to reduce chromatic aberrations and sensitivity to position errors. The beams must also be separated as near as possible to the interaction point to minimize the spacing between successive proton bunches and still avoid unwanted crossings.

Three different insertion designs have been proposed in the SSC[1] to try to satisfy these constraints. In the first proposal, the quadrupoles are in front of the separating magnets (see Fig. 1, copied from Reference 1) leading to small values of β at the crossing point (2m) but the minimum bunch spacing is relatively long (160m). The second proposal is a modification of the first where a small (0.2mr) crossing angle is introduced between the beams. The minimum bunch spacing can then be reduced to about 50m with the same beta values at the crossing point. However, the crossing angle increases the cross-section of the beams at the collision point by an amount depending on the bunch length and can also reduce the maximum attainable beam-beam tune shift due to the excitation of synchro-betatron resonances. In the third proposal,[2] the bending magnets are placed in front of the quadrupoles so that the minimum bunch spacing is reduced to only 30m. Since the quadrupoles are now considerably further away from the crossing point the maximum beta values are increased (1760m to 3000m) compared with the first two schemes for the same beta value at the crossing point. In addition, special slim quadrupoles are required which complicates the already difficult construction problems.

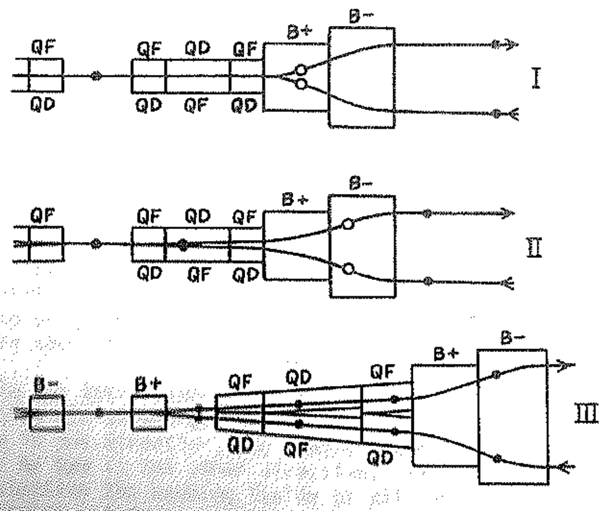

FIG 1. Three interaction region configurations for p-p collisions.

These three schemes have one feature in common, the focusing and separation are provided by separate elements. In the present proposal, the possibility of combining these functions into the same magnetic elements is examined. Combined function superconducting magnets have been proposed[3] but the maximum attainable focusing gradient is considerably reduced in this case. Even in a 'pure' quadrupole, however, the field off-axis contains both dipole and quadrupole components and in this paper the possibilities of using offset quadrupoles are examined.

Basic Principles

The starting point for the insertion is shown schematically in Fig. 2. It is based on the first proposal discussed above using a quadrupole triplet to provide the focusing. Since the two beams have the same polarity but travel in opposite directions, the focusing action is inverted for the two beams (FDF for one, DFD for the other). Two common bends are used behind the triplet to obtain the beam separation required in the rest of the ring (typically 16-18cm for 2-in-1 magnets). These magnets will not be discussed further as it is the triplet that is of interest here.

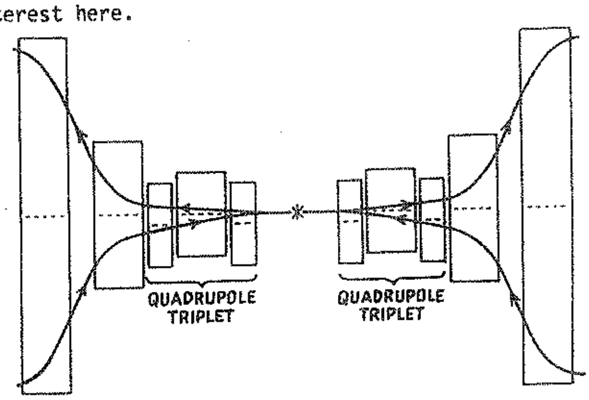

FIG. 2. Schematic layout of insertion with offset quads.

For the purposes of the examples presented below the values shown in Table 1 have been assumed. To get a first feeling of the orders of magnitude involved, a 5mm offset in a quadrupole with a gradient of 300T/m gives a field of 1.5T. If this were a constant over the 6m quadrupole it would bend 10TeV beams by 0.27mrad -a value not dissimilar to the 0.2mrad assumed for the crossing angle in the second proposal discussed above.

TABLE 1. Assumptions for Examples

Free space	±10m
Inner quad length	6m
Quad-quad space	1m
Central quad length	12m
Quad-quad space	1m
Outer quad length	6m
Quadrupole gradient	300T/m
Beam energy	10TeV

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This assumption of constant field is only very approximate in the present case since the beanms are deflected by an amount similar to that of the original displacment. The trajectories have therefore been tracked using DECAY TURTLE[4] which can be used to evaluate offset elements.

In the first example of insertions with offset quadrupoles it was assumed that the whole triplet is shifted by 5mm. To first order, the beams then see fields of alternating sign with the central magnet twice the length of the outer pair. This is not dissimilar to the layout of a wiggler magnet in an electron storage ring where the net displacement and deflection of the orbit is zero. In the present case, the beam bent away from the axis sees a stronger field in the central quadrupole while the beam bent towards the axis sees a weaker field. The actual trajectories are shown in Fig. 3 where it can be seen that there is a net displacement of the two beams (equal to within the accuracy of the program) and a net deflection slightly different for the two beams. In the center of the triplet the two beams are separated by about 3.5mm which could be used to avoid unwanted crossings between bunches about 50m apart. The maximum excursion of the beams relative to the quadrupole axis is 6.9mm in the central quadrupole and unfortunately occurs for the beam having its maximum betatron amplitude at the same place.

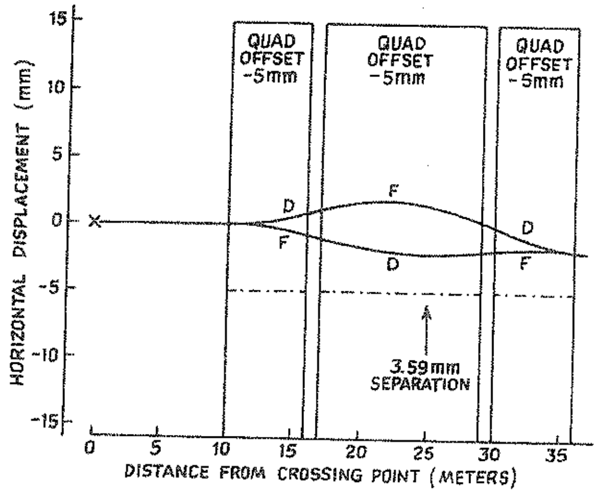

FIG 3. Offset quadrupole insertion, example 1.

In the second example, only the first quadrupole is offset and the beams then 'drift' through the other two quadrupoles of the triplet. By 'drift' I mean that the two beams see fields of opposite sign and are therefore bent in the same direction and, in the first approximation, by the same amount. The actual trajectories are shown in Fig. 4 where the separation at 25m (corresponding to 50m bunch spacing) is now 6.5mm. The maximum displacement of the beams is now only 5.5mm in the central quadrupole and occurs where the betatron amplitude is less than its maximum. The maximum excursion in the outer quadrupole is 8.5mm at a place where the beam size is close to its maximum.

In the third example the quadrupoles in the insertion are staggered, the outer pair being offset by 5mm in one direction, the central quadrupole being offset by 5mm in the other direction. In the first approximation the bending fields of all the quadrupoles reinforces and the deflections are greater than in the two previous cases. The actual trajectories are shown in Fig. 5 and the separation at 25m is now 9.3mm. The maximum excursions are also considerably increased to more than 14.2mm in the central quadrupole and 16.5mm in the outer quadrupole but these maximum values occur in both cases for the smaller of the two beams.

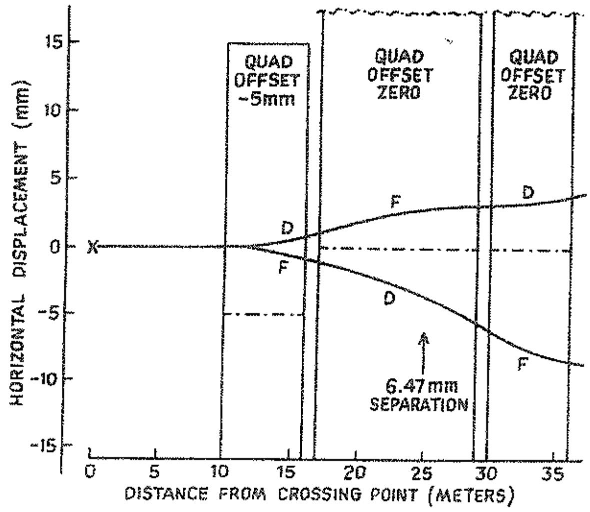

FIG 4. Offset quadrupole insertion, example 2.

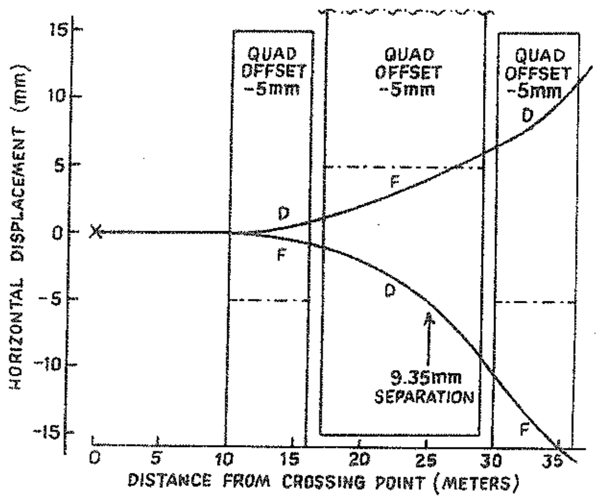

FIG. 5. Offset quadrupole insertion, example 3.

From these examples, the criteria for choosing a reasonable design can be established. The first quadrupole can be offset by up to about half its radius without causing aperture problems. The second and third quadrupoles should each be positioned to be roughly centered around the diverging beam to minimize the aperture requirements for a given separation. The fourth example shown in Fig. 6 has been chosen more or less to meet this criteria. The inner and outer quadrupoles are offset by 5mm in the same direction while the central quadrupole has no offset. The separation at 25m is about 6.5mm as in the second example but the maximum excursion is now only 5.5 mm in the central quadrupole and 7.6mm in the outer quadrupole and in both cases the maximum occurs for the smaller of the two beams.

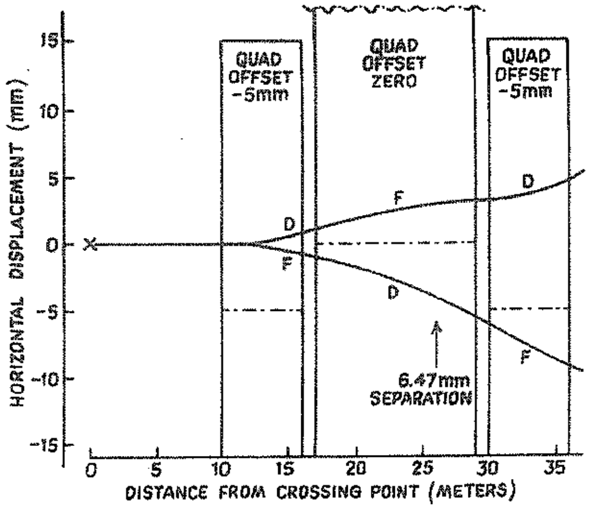

FIG. 6. Offset quadrupole insertion, example 4.

This layout will therefore be retained but before going further the amount of separation required must be evalulated.

Beam Separation

The separated beams suffer a tune shift which adds to that due to the wanted collision. The criteria for the beam separation should therefore be expressed as a ratio between the remnant tune shift of the closest unwanted crossings (one either side) to the tune shift of the wanted collisions.

The tune shift of the colliding bunches can be expressed as

$$\Delta Q^*_z = \frac{r_p N_b}{2\pi\gamma} \cdot \frac{\beta^*_z}{\sigma^*_z(\sigma^*_x + \sigma^*_z)}$$

where

r_p is the classical radius of the proton,
N_b is the total number of particles per bunch,
γ is the relativistic factor,
β^*_z is the vertical beta function at the crossing point, and
$\sigma^*_{x,z}$ are the rms beam radii.

This can be simplified in the present discussion where it is assumed that

$$\sigma^*_x = \sigma^*_z = \sigma^*$$

$$\beta^*_x = \beta^*_z = \beta^*$$

and the emittance of the beam ϵ is defined as

$$\epsilon = 4\pi\gamma\sigma^{*2}/\beta^* .$$

Then the vertical and horizontal tune shifts are also equal and given by

$$\Delta Q^* = r_p N_b/\epsilon .$$

The tune shift of the separated beams is given to to a sufficient approximation for well separated beams as

$$\Delta Q^{sep}_{x,y} = \frac{r_p N_b}{2\pi\gamma} \cdot \frac{\beta_{x,z}}{\delta^2}$$

where δ is the beam separation. So the important ratio is then given by

$$\frac{\Delta Q^{sep}_{x,y}}{\Delta Q^*} = \frac{\epsilon}{2\pi\gamma} \cdot \frac{\beta_{x,z}}{\delta^2}$$

With the proposed layout of the triplets either side of the crossing point, the values of β_x and β_z are exchanged on the two sides of the insertion. Since it is the sum of the two unwanted collisions that is important we arrive at the final forumla

$$\frac{\Delta Q^{sep}}{\Delta Q^*} = \frac{\epsilon}{2\pi\gamma} \cdot \frac{\beta_x + \beta_z}{\delta^2} \qquad (1)$$

where

ΔQ^{sep} is the total tune shift due to the two unwanted crossings either side of the insertion, and

β_x, β_z are the horizontal and vertical beta values at the unwanted crossings.

Since the additional tune shift is inversely proportional to the energy, the criteria for the separation comes from the low energy region. During injection and ramping the insertion would probably be detuned (i.e., β^* increased to reduce the maximum beta values in the triplet) and the beams could also be separated magnetically rather easily. It is therefore the lowest operating energy that is important and I assume this to be equal to the maximum energy of the Tevatron, i.e., 1 TeV per beam.

Then to get an idea of the orders of magnitude involved, take

$$\epsilon = 10\ \pi\ \mu m$$

$$\beta_x + \beta_z = 1000 + 500 = 1500\ m$$

$$\delta = 5\ mm$$

$$E = 1\ TeV$$

then

$$\Delta Q^{sep}/\Delta Q^* = 0.29$$

which is probably acceptable. At 10 TeV the additional tune shift is less than 3.5% which is completely negligible.

LHC Insertion

As seen above, the beam separation required increases at low energy as does the beam size. The quadrupole aperture is therefore determined by the requirements at the lowest operating energy. The maximum beam size corresponding to the emittance and beta values given above is 1.9mm and if 8 σ is required for good lifetime, then the maximum beam aperture requirement is ±15mm. The inner radius of the vacuum chamber is likely to be about 20mm leaving 5mm clear for the offset trajectories. In example 4, which will serve as the basis for the practical design, it was seen that the maximum excursion was of the same order of magnitude as the beam separation obtained 25m from the crossing point. We therefore aim for a 5m separation at this point.

TABLE 2. Assumptions for the LHS Insertion

Free space	10.0m
Inner quad length	8.2m
Quad-quad space	1.0m
Central quad length	12.85m
Quad-quad space	1.0m
Outer quad length	7.0m
Beam energy	1.0TeV
Quadrupole gradient	33.36T/m
Quadrupole aperture	±20.0m
Beam emittance	10 π μm
Beta value at crossing	1.0m

The parameters adopted are given in Table 2 (the quadrupole parameters were provided by Mario Bassetti) and the trajectories are shown in Fig. 7. It can be seen that the beams just fit into the ±20mm aperture with very little to spare. If colliding beams of 1 TeV are really required or if a larger emittance should be accommodated then this aperture should be increased or the β^* must be increased. For collisions at the top energy this insertion would meet all the requirements and would improve the luminosity by at least a factor 2 over the previous insertion designs.

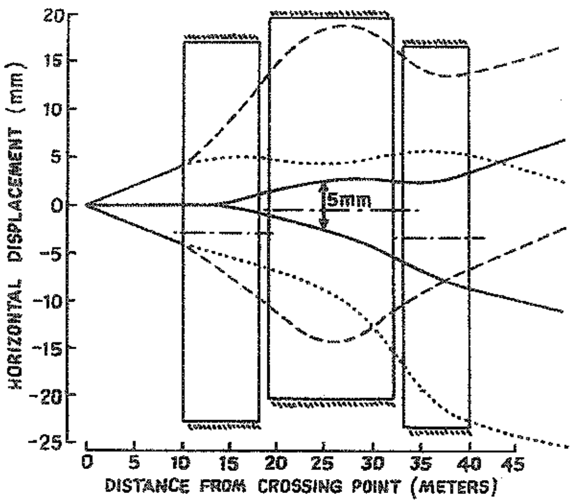

FIG. 7. Proton-proton insertion for the LHC.

Acknowledgements. I have profited from many helpful discussions with Steve Meyers, Alasdair Smith, and Tom Taylor who have helped clarify my ideas.

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